A TECHNICAL ANALYSIS OF THE BUNCEFIELD EXPLOSION AND FIRE

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In December 2005, a succession of events led to the release of large quantities of gasoline from a bulk storage facility in Buncefield near the Heathrow airport in UK. This paper provides a technical analysis of the reasons behind the extent of the flammable vapor cloud that may have accumulated and the mechanism by which the overpressure was generated. This paper also summarizes some of the past incidents involving open-air vapor cloud explosions and the apparent similarities and parallels with the Buncefield fire.

The mechanism of the gasoline release and drop from height leads to vapor release and by the time the release hits the ground, most of the vapor is formed. The turbulence of the release itself created turbulence that caused air entrainment. After ignition, the well mixed fuel-air vapor cloud attained higher flame speeds caused by the congestion and turbulence thus further exacerbating the intensity of the explosion.

KEYWORDS: Buncefield, vapor cloud explosion, gasoline explosions, learning from the past, turbulence, congestion

> "*Forgetfulness is one of the great sins of our time. People block out remembrance of difficult times, of failures, of their own weakness.*"
>
> —*Albert Friedlander*
>
> *Lessons From Disaster – How Organizations Have No Memory And Accidents Recur*
>
> —*Trevor Kletz*

BACKGROUND

In the early hours of Sunday, December 11, 2005, a number of explosions occurred at Buncefield Oil Storage Depot, Hemel Hempstead, Hertfordshire, United Kingdom. At least one of the initial explosions was of massive proportions and there was a large fire, which engulfed a high proportion of the site. This was the largest fire in Europe for 50 to 60 years. Over 40 people were injured; fortunately there were no fatalities. Significant damage occurred to both commercial and residential properties in the vicinity and a large area around the site was evacuated on emergency service advice. A survey of 761 private householders in the area surrounding Buncefield suggested 76% had experienced some damage. This mainly comprised broken glass, damaged window and door frames, roofs and cracks in walls and ceilings (http://www.buncefieldinvestigation.gov.uk/index.htm). The fire burned for several days, destroying most of the site and emitting large clouds of black smoke into the atmosphere. Some 2,000 homes were evacuated and 92 neighboring firms were affected by Europe's largest peacetime fire (http://www.buncefieldinvestigation.gov.uk/index.htm). Property damage was reported as far away as 10 km. The clean-up of 26 million liters of stored contaminated water used to fight the blaze, as well as ground water contaminated by diesel entering a borehole, remains a concern. During the year some 800,000 liters of stored water was found to have leaked into the Colne, a tributary of the Thames. Environment Agency officials became aware of the presence of perfluorooctane sulphonate, or PFOS, a toxic substance used in some firefighting foams that does not break down in the environment. Special treatment and disposal of the most contaminated firewater, stored at the Maple Cross treatment works, started in November 2006[1–6].

Three lines supplied the products from different refineries. As a result of the incident, three major lines taking the product to customers went out of service. Of these three outgoing lines, one dedicated line to each of Gatwick and Heathrow airports, i.e., London's 2 largest airports. As a result, fuel rationing had to be implemented at Heathrow. Though the Buncefield site contained operations by a number of companies, the incident started at Hertfordshire Oil Storage Ltd., a COMAH site with 200,000 tonnes inventory[6].

An initial report published identified areas of concern related to the design and operation of storage sites, the emergency response to incidents and advice given to planning authorities about risks to proposed developments around depots similar to Buncefield[3]. Investigators said an apparently faulty gauge and safety devices led to the overfilling of fuel storage tank 912 leading to an escape of unleaded petrol and the formation of a cloud of flammable vapor that ignited. A separate report by Hertfordshire Fire Service, which was aided in the emergency response by crews from across England, came up with 30 recommendations (http://www.hertsdirect.org/buncereport). Among these were suggestions for a national system of incident command support teams, earpieces for radios to enable communication while wearing a helmet and a proposal that early consideration needs to be given to deployment of national resources.

Immediately following the incident, a number of statements were made that the Buncefield fire was "one-of-a-kind" and such a catastrophic incident in an oil depot had never occurred before. The argument being that since it was a "one-of-a-kind" incident, there was no way to account for such an incident in the design, construction, and operation of the facility and emergency response plans. However, a review of literature and past incidents makes it abundantly clear that incidents in tank farms and oil storage depots are quite common. In fact, there are at many incidents that have significant similarities with the Buncefield.

HAZARDS OF OIL STORAGE

It has long been recognized that fires or vapor cloud explosions can occur as a result of spillage of fuels or flammable materials from aboveground storage tanks (AST's) in tank farms. Common causes that could unleash spills include overfilling, leaking from worn-out and corroded containment, and loss of containment due to pipeline ruptures. Another hazard that is not always recognized is the generation of combustible vapors that can be formed from the mixtures of combustible liquids stored in AST's[7]. AST's are utilized not only for the storage of pure flammable/combustible liquids but also for the combustible liquid mixtures, which is the case with slop tanks containing water/oil mixtures. In slop tanks, oil and water are separated. For this separation it is necessary to heat the oil/water mixture but sometimes this could lead to temperature differences between the layers formed and in this way it is possible to have vapor formation. These conditions could lead to two phases overflowing on the top of the tank and subsequent formation of a fuel vapor cloud[8].

Vapor cloud explosion is not a common form of explosion but, it is cataloged as the most dangerous and destructive explosions in the chemical and petrochemical industries[9]. Vapor cloud explosions are catastrophic and destructive because the vapors released can disperse to other locations and upon contact with an ignition source, can lead to a major explosion followed by a large fire. The series of events leading to the fire itself is not so simple. Actually, a vapor cloud forms only if the amount of vapor released is enough. Once the vapor cloud is formed and encounters an appropriate ignition source, the result could be a devastating explosion that is generally followed by a large fire. All the factors mentioned previously could be present in tank farms making it possible for a vapor cloud explosion to occur. It is a common misconception that if one tank is engulfed by fire, it is probably easy to control the fire. However, in a tank farm where many tanks are situated next to each other, adjacent tanks could be easily engulfed and lead to secondary fires or explosions due to the energy released from the first event.

CHRONOLOGY OF EVENTS

The chronology of events presented here is summarized from various references[1–6].

At or about 7 pm on December 10, 2005, Tank 912 started receiving a consignment of 8,400 m^3 unleaded motor fuel. At the commencement of receipt of this consignment, the tank gauging records show that Tank 912:

- contained 1,079 m^3 of unleaded motor fuel; and
- had ullage of 4,971 m^3.

The flow rate to Tank 912 was initially 550 m^3/hr. From approximately 3 am on December 11, 2005, the Automated Tank Gauging System indicated that the level for Tank 912 remained static at two-thirds full. During this time the tank temperature for Tank 912 continued to rise. At approximately 5:35 am on December 11, 2005, the fuel in Tank 912 began to overflow.

The site and neighboring office buildings were equipped with more than a dozen CCTV cameras that recorded images of a visible mist shortly before the explosion. Witness statements also corroborate the spread of a mist-like cloud and reports of the smell of gasoline. At approximately 5:53 am on December 11, 2005, the flow rate to Tank 912 increased to 890 m^3/hr. By about 6 am on December 11, 2005, approximately 300 metric tons of unleaded gasoline had overflowed from Tank 912.

At around 6 am on Sunday, December 11, 2005, an explosion occurred at Buncefield when part of the vapor ignited. The first explosion was followed by further explosions and a large fire which involved over 20 large storage tanks of various sizes.

A plot plan of the Buncefield site is shown in Figure 1 and a schematic of tank 912 which overflowed is shown in Figure 2.

THE RELEASE SCENARIO

The nature of the liquid release plays a significant role in determining the extent of the vapor cloud and the quantity of aerosol droplets that may be entrained in the vapor. For example release of a liquid from a hole in the tank near the ground would produce relatively low volumes of vapor and liquid droplets as compared to liquid releases from a height[10]. As described in the BMIIB reports and Atkinson and Gant[11], the Buncefield tank 912 was a fixed roof tank with a number of open breather vents close to the edge of the tank at a spacing of around 10 m around the perimeter. When the tank was overfilled, liquid flowed out of the open vents, spreading a little before it reached the tank edge. A proportion of the liquid release was directed back on to the wall of the tank and a proportion simply flowed over the edge. Tank 912 also had wind girders part way down the tank wall to stiffen the structure. Any liquid falling close to the tank wall would have hit this girder and be deflected outwards, away from the tank wall. This outward spray then intersected the cascade of liquid from the top of the tank. With these features present, the spray typically would extend to a significant

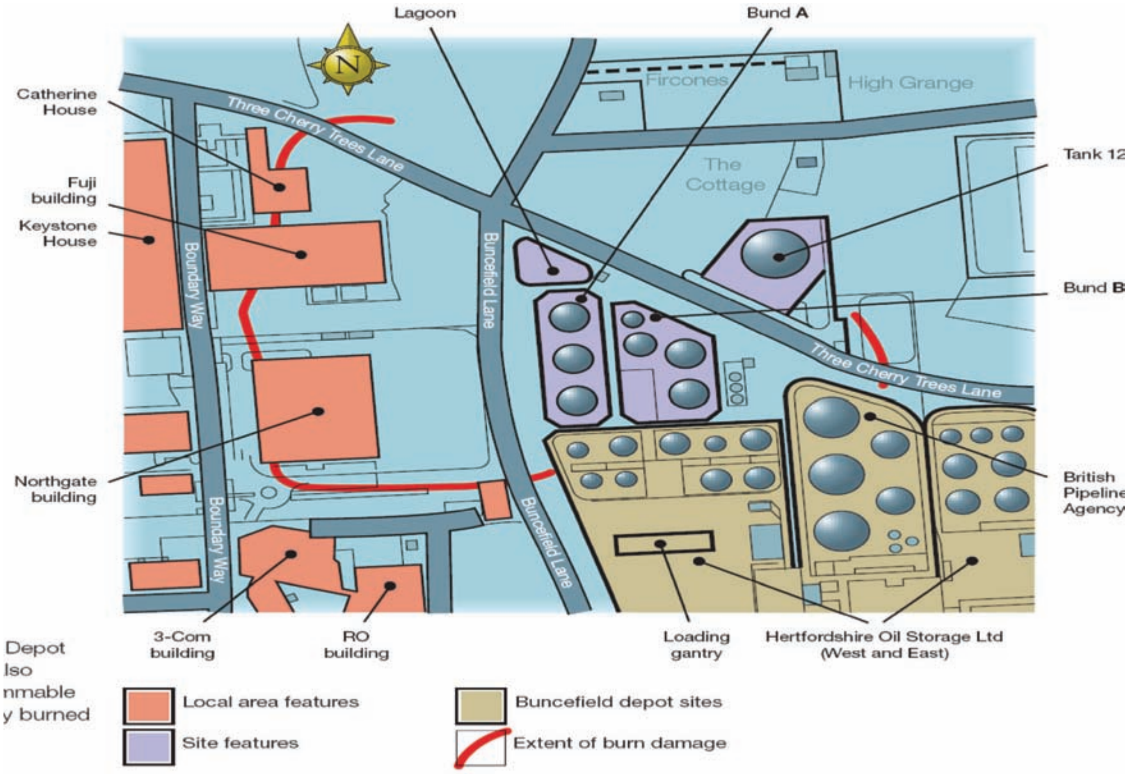

Figure 1. Plot plan of Buncefield site. (Source: http://www.buncefieldinvestigation.gov.uk/images/index.htm)

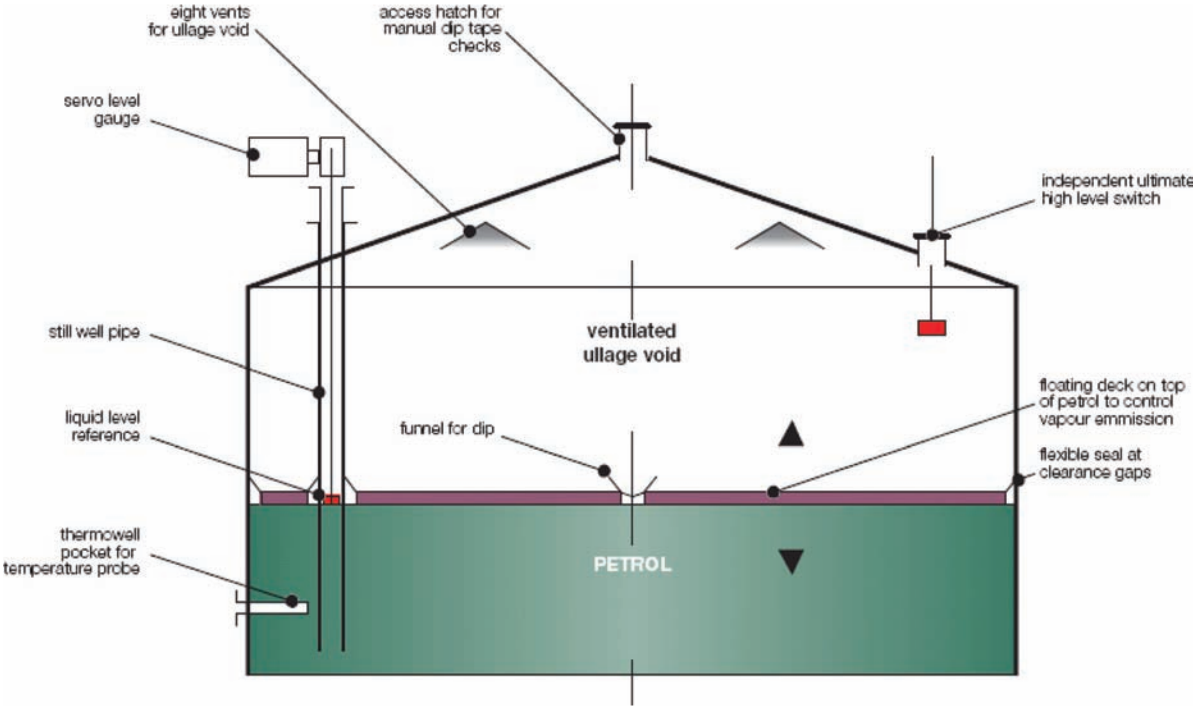

Figure 2. Schematic of Tank 912 which overflowed from the 8 breather holes. (Source: http://www.buncefieldinvestigation.gov.uk/images/index.htm)

area around the tank perimeter (see p. 23 of Atkinson and Gant[11]).

As the intermingling sprays of the released liquid fell to the ground, large scale liquid strings were formed which then start dividing into large droplets. Some of the initial liquid fragments rapidly shattered to form a range of secondary droplets[12]. There will also have been formation of aerosol droplets of various sizes.

While the phenomenon described above was occurring, air was drawn into the liquid cascade and vapor was also being produced from the liquid evaporating and mixing with the air. Some liquid droplets remained suspended in the vapor flow as it impacted on the bund wall or other tanks within the bund. Individual falling droplets dragged the air within the cascade downwards and air would have been drawn in through the sides to compensate. It is likely that the splash zone at the base of the tank was an additional area where vapor and very finely divided liquid were vigorously mixed for a significant period of time. Inevitably, given the composition and properties of the released fluid, there would have been vaporization. Because of the drop from height and the droplet formation, the vaporization rate was enhanced.

Given the release of 300 tons of gasoline from Tank 912, and the release scenario described above, it was quite likely to have expected the formation of the cloud size that did form.

THE FORMATION AND SIZE OF THE CLOUD

The intensity of the explosion and the resulting overpressure is dependent amongst other things on the amount of flammable mixture (which is a function of the amount of released fuel), the length of the release duration, and the fact that it was falling in droplets from a height. The BMIIB Third Progress Report[5] speaks of the vapor cloud covering 80,000 m^2. In fact, as indicated by Gant and Atkinson's Report, the vapor cloud was probably larger[13] (p. 50 para 4.1):

> "*The CCTV footage taken in the minutes leading up to the explosion at Buncefield showed a visible low-lying mist spreading out from HOSL Bund A and covering a wide area, roughly 500 × 400 meters in extent… The final images recorded before the explosion show that the mist layer had reached over 4 meters deep immediately adjacent to HOSL Bund A and between 2 and 3 meters deep in the main Northgate and Fuji car park areas. The extent of the mist layer correlates reasonably well with evidence of burn damage.*"

Thus, the Gant and Atkinson report would seem to indicate that the cloud covered at least a large part of a 200,000 m^2 area (this is a conservative number from the two numbers mentioned in the Gant and Atkinson report). The extent of the cloud is also corroborated by the witness accounts which include seeing the mist, smelling the gasoline, and cars revving on their own even when the ignition was turned off.

The witness statements and CCTV images seem to corroborate the Gant and Atkinson report[13] that the cloud may have covered an area as large as 200,000 m^2. Whatever the actual size of the cloud, this was a massive cloud, both absolutely and as compared with the evidence from other incidents, and an important reason why the explosion was so large. There is evidence from some of the earlier incidents of much smaller clouds producing violent explosions, as one can see from the descriptions in Lenoir and Davenport's list of previous incidents[14]. For example, at page 15 they describe a 195 m × 116 m cloud that broke windows 6.4 km away, at Baton Rouge in 1951. There is frequent reference to other small clouds creating widespread damage. From other materials, one can see for example that the St Herblain vapor cloud (discussed in detail later) was 23,000 m^3 and the Conoco Humber vapor cloud was 175 m × 80 m[15]. In comparison, for the Buncefield incident, as stated above the estimates of the area of the vapor cloud vary between 80,000 m^2 to 200,000 m^2.

With regard to the development of the vapor cloud, the height of the cloud is also important. At 5:38 am, CCTV footage showed a 1 m deep vapor cloud flowing out of the north-west corner of bund A. At 5:46 am, the vapor cloud was 2 m deep flowing in all directions (p. 5 of the BMIIB Third Progress Report[5]). At the time of the explosion it was reported that the visible mist varied between 1 m to 7 m: p. 12, para 40 of the BMIIB Third Progress Report[5] discusses the spread of the vapor cloud and its depth of 1 m in the area between bund A and the loading gantry, and 5 to 7 m in Three Cherry Trees Lane. That Report went on to say:

> "*As described in the first progress report, eyewitness accounts and CCTV footage show a white mist or thick fog on the north and west sides of the HOSL West site, spreading out from bund A (around Tanks 910, 912 and 915). By the time of the main explosion, the edge of this cloud had almost reached Boundary Way to the west of bund A and wisps of mist had just started to arrive at the tanker loading gantry to the south. To the north, it had flowed beyond Cherry Tree Lane. To the east, the mist can be seen on CCTV at the BPA site, but not further east at the HOSL East site.*"

Page 12, para 38 of the BMIIB Third Progress Report[5] discusses the formation of the vapor cloud and the mechanism that causes it to be visible on the CCTV:

> "*The free fall of fuel droplets through the air also leads to entrainment of air and mixing between the air and fuel vapor. Calculations based on a simplified composition of unleaded petrol suggest that the ambient air already at*

> *0°C and fully saturated with water vapor, would have cooled below zero by a further 7–8°C from fuel evaporation. As a result, roughly half the initial water content of the air would precipitate as an ice mist, and this mist would persist even as the vapor is diluted. This is consistent with the cloud of mist highly visible on CCTV cameras. It supports the contention that the mist can be used as an indicator for determining the size of the fuel/air vapor mixture created by the overfilling and how it was dispersed.*"

Based on the above discussions, it is reasonable and conservative to assume that the average height of the vapor cloud was at least 2 m. Also as described earlier, estimates of the area covered by the cloud vary between 80,000 m^2 to 200,000 m^2. Based on reviewing CCTV footage and witness statements it seems that the vapor cloud was larger than 80,000 m^2 but probably somewhat smaller than 200,000 m^2. So, a conservative estimate of the area covered by the cloud be taken as 150,000 m^2. That would put the volume of the cloud between 160,000 m^3 to 300,000 m^3.

The nearest meteorological measurements indicate that on the morning of the incident, the weather was calm, cold, stable, and humid (similar to the weather conditions at the St Herblain incident). The weather on the night of the release was Pasquill stability category F, with a zero or very near zero wind speed (p. 17 para 62 of BMIIB Progress Report dated 21 February 2006[3]).

As described in the BMIIB reports, when the liquid gasoline cascaded down from the roof of the tank, evaporation of the more volatile fractions would lower the temperature. This caused temperatures to drop below 0°C and perhaps as low as minus 10°C in the surrounding gas phase. A sudden drop in temperature caused the water vapor to condense out of the air and essentially form a fog. There would be significant turbulent mixing taking place within the bund due to the liquid sprays which mixed the fog with the gasoline vapor (see section 2.2. of BMIIB Third Progress Report dated 9 May 2006[5]). Energetic breakup of the droplets produced a significant quantity of smaller aerosolized droplets which were then entrained with the vapor/air mixture. Some of the larger droplets rained out and accumulated in the liquid pool while the smaller droplets were entrained in the vapor/air mixture. The presence of the so-called "aerosolized droplets" contributed to the intensity of the VCE for the simple reason that the cloud contained much more energy per unit volume. The phenomenon of aerosol formation has been discussed by Bai and Rusche[12]. It was entirely to be expected in a release scenario such as the one at Buncefield. Lechaudel and Mouilleau in their paper on the St Herblain incident (discussed later) also report the formation of aerosol[16].

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TERMINOLOGY

Various publications such as the Gas Explosions Handbook ("GEH")[17], Explosions in the Process Industry ("EITPI")[18] and the Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs ("the Guidelines")[19] provide definitions for commonly used terminology for vapor cloud explosions.

VAPOR CLOUD EXPLOSIONS

A vapor cloud explosion may be simply defined as an explosion occurring outdoors, producing a damaging overpressure. It begins with the release of a large quantity of flammable vaporizing liquid or gas from a storage tank, process or transport vessel, or pipeline.

Should the cloud be allowed to form over a period of time within a process area, then subsequently ignite, blast pressures that develop can result in extensive, widespread damage. Ignition delays of 1 to 5 minutes are considered the most probable for generating vapor cloud explosions, although major incidents with ignition delays as low as a few seconds and greater than 30 minutes are documented. The blast effects produced by vapor cloud explosions can vary greatly and are determined by the speed of flame propagation. In most cases, the mode of flame propagation is deflagration. Under extraordinary conditions, a detonation might occur.

A deflagration can best be described as a combustion mode in which the propagation rate is dominated by both molecular and turbulent transport processes. In the absence of turbulence (i.e., under laminar or near-laminar conditions), flame speeds for normal hydrocarbons are in the order of 5 to 30 meters per second. Such speeds are too low to produce any significant blast overpressure. Thus, under near-laminar flow conditions, the vapor cloud will merely burn, and the event would simply be described as a large flash fire. Therefore, turbulence is always present in vapor cloud explosions. Research tests have shown that turbulence will significantly enhance the combustion rate in deflagrations. These mechanisms may cause very high flame speeds and, as a result, strong blast pressures.

In the extreme, the turbulence can cause a sufficiently energetic mixture to convert from deflagration to detonation. This mode of flame propagation is attended by propagation speeds in excess of the speed of sound (2 to 5 times the speed of sound) and maximum overpressures of about 18 bar (260 psi). Once detonation occurs, turbulence is no longer necessary to maintain its speed of propagation. This means that uncongested and/or quiescent flammable portions of a cloud may also contribute to the blast. Note, however, that for a detonation to propagate, the flammable part of the cloud must be very homogeneously mixed. Because such homogeneity rarely occurs, vapor cloud detonations are unlikely.

INCIDENTS INVOLVING VIOLENT VCE'S

The following provides a listing of incidents involving violent VCE's, where off-site property damages have been sustained at distances up to 10 km:

- Portland 1954 (glass breakage to 3.2 km) (p. 15 of Lenoir and Davenport[14]).
- Pernis 1968 (diameter of the vapor cloud was 90–140 m and windows were broken several km away) (Appendix 1 of Mannan20).
- Laurel 1969 (broken windows at up to 4.8 km) (p. 18 of Lenoir and Davenport[14]).
- Baton Rouge 1971 (window breakage at up to 4.8 km) (p. 19 of Lenoir and Davenport[14]).
- Climax 1974 (directional blast, possibly detonation, producing window breakage at up to 10–11 km) (p. 20 of Lenoir and Davenport[14]).
- Rosendaal 1975 (windows broken to range of 900 m) (p. 21 of Lenoir and Davenport[14]).
- Pitesti 1978 (windows broken at up to 9.5 km) (p. 22 of Lenoir and Davenport[14]).
- Texas City 1979 (windows broken at up to 1–1/2 miles) (Marsh[21]).
- Newark 1983 (windows broken at up to 5.6 km) (p. 23 of Lenoir and Davenport[14], other references[10,22–25]).
- Romeoville 1984 (windows damaged at up to 9.6 km) (p. 23 of Lenoir and Davenport[14].
- Naples 1985 (glass broken at 1 km, observable minor effects at up to 5 km) (Maremonti et al.[25], other references[21, 26].
- Antwerp 1987 (glass damage at up to 10 km) (p. 24 of Lenoir and Davenport[14].
- Norco 1988 (property claims for off-site damage at up to 10 km) (Marsh[21]).
- Ufa 1989 (windows broken at up to 13 km) (p. 25 of Lenoir and Davenport[14]).
- Baton Rouge 1989 (windows broken at up to 10 km) (p. 25 of Lenoir and Davenport[14], other references[21].
- St Herblain 1991 (windows broken within 2 km radius) (Lechaudel and Mouilleau[16]).
- La Mede 1992 (windows broken at up to 10 km) (Marsh[21]).
- Texas City 2005 (windows broken at 1.2 km) (CSB[27]).

VIOLENT VCES INVOLVING GASOLINE VAPOR

This section provides brief descriptions of violent VCE's involving gasoline vapor.

PERNIS, NETHERLANDS, 1968

Lenoir and Davenport[14] and Lees 3rd Edition[20] provide details of a catastrophic incident in 1968 in Pernis, Netherlands involving 80 tanks which burned down as a result of a series of explosions followed by fires. Huge amounts of glass windows in the adjacent community were broken due to explosion blast waves. The projectile fragments caused 2 deaths and 85 injuries. This devastating vapor cloud explosion occurred due to the evaporation and subsequent vapor cloud formation of the light hydrocarbons in an emulsion composed of oil and water. This emulsion was heated and massive boiling occurred. The light hydrocarbons were released through the vents of the slop tank resulting in a two-phase overflow. Although the ignition source is not known, the damage caused by the explosion was quite extensive[20]. The size of the cloud was reported to be between 6,364 m^2 to 15,400 m^2.

Lessons from this incident were that releases of light hydrocarbons can lead to violent VCEs, that windows were broken several km away and a relatively smaller vapor cloud produced damage over a wide area.

ROSENDAAL, NETHERLANDS, 1975

In 1975, in Rosendaal, Netherlands a release of gasoline from a line leak occurred during atmospheric conditions of low wind and an inversion layer. The leak lasted between 8–17 minutes resulting in the release of 25–50 tonnes of gasoline, which was then ignited by an unknown ignition source. The resulting VCE resulted in two fatalities and windows being broken 800 m away14.

The lessons learned include, 1) gasoline at ambient temperature can generate a vapor cloud of sufficient size to support a VCE, and 2) damage from such a VCE can be widespread.

CALIFORNIA, 1981

In February 1981, an explosion and a fire occurred at a bulk oil terminal in California when 18,000 gallons of gasoline overflowed a storage tank and ignited during a fuel transfer operation. The incident began when pumping operations were started to transfer unleaded gasoline through pipelines to a storage tank on a tank farm. Unfortunately, the tank capacity had been miscalculated and more than 18,000 gallons of gasoline were pumped through the tank and released. The tank was equipped with a high level alarm, but it had been out of service for several months. The rich fuel-air mixture resulting from the overflow engulfed the facility with a low-hanging vapor cloud. Upon ignition, the ground shock and explosion were felt more than 1,600 m away from the terminal[28].

This incident was another example of a violent VCE that occurred in a tank farm operation leading to widespread damages.

NEWARK, NEW JERSEY, 1983

On January 7, 1983, an incident occurred in Newark, New Jersey, in which several minor initial explosions were followed by a major explosion with a large fire that burnt for approximately 48 hours[22]. The size of the cloud was estimated to be between 27,000 m^2 and 54,000 m^2. The incident caused one death and 24 injuries, destroyed four gasoline storage tanks, and released three million gallons of gasoline. The incident occurred when one of the three tanks in the same dike area was overfilled. The particular tank was being filled from an underground pipeline while its gasoline content was being transferred to another remote tank simultaneously. A vapor cloud was formed as a result of the evaporation of the light compounds of gasoline, which was probably ignited by a nearby incinerator. Approximately 200 metric tons of gasoline was released and the ignition source is believed to have been 300 m away. The area between the overfilled tank and ignition source (and the remainder of the storage facility) was generally open, but covered by scrub[22,24].

The weather conditions during the incident are reported as wind speeds of 1–5 mph[10] and very light and nearly still weather conditions[22]. At midnight the winds were listed as negligible, although prior to the incident they were listed as variable from a southern direction at 3 mph[23].

The blasts appeared to have had a great deal of force, in that tank 9, a remote and empty storage tank some 360 m away was flattened by the impact, and tank 4, some 450 m away, also was damaged. Other reported damage included flattened railroad freight cars and destruction and fires at a nearby drum refinishing plant. Also, windows were broken 5.6 km away. At the truck terminal building, large tank trucks were tossed about, several automobiles were incinerated, and numerous fires ignited in the general area. In addition, the impact of the blast damaged several structures at surrounding industries, quite similar to the damage seen in the Buncefield incident.

Lessons learned from this incident include: 1) releases of cold gasoline can lead to violent open-air explosions, 2) "*discharges from a height and a spill down the side of a tank will help formation of a vapor cloud[10]*", 3) a vapor cloud may drift a considerable distance to an ignition source, 4) significant overpressures can result even where there are large apparently open spaces (also this indicates not only that scrub will provide confinement/create turbulence, but that obstacles on the far side of such spaces can also provide significant confinement where there is a large spill and vapor cloud), and 4) widespread overpressure damage may ensue. As the Loss Prevention Bulletin 057[23] stated at p. 18, "*the severity of each incident indicates a great potential for death and destruction in any future occurrence*".

NAPLES, ITALY, 1985

On December 21, 1985, a vapor cloud explosion occurred in a fuel storage area located in the vicinity of Naples, Italy[25]. Twenty four of the thirty two tanks at a marine petroleum products terminal were destroyed by a fire that began with a tank overfill. The release continued for about 1.5 hours resulting in a 45,000 m^3 vapor cloud, which was ignited by an unknown source. Almost immediately twenty of the tanks were involved in a massive fire. The devastating explosion destroyed the terminal buildings and extensively damaged nearby industrial and residential structures. The accident originated from a spill of gasoline that occurred during a filling operation. Gasoline overflowed through the roof of tank no. 17 and the total amount of spilled fuel was estimated to be about 700 tons. The strong explosion and the following fire, which lasted over one week, destroyed all the buildings and the equipment within the area. The associated blast wave caused at least four fatalities, whereas minor effects were observed up to 5 km away. The incident also caused 170 injuries and the evacuation of about 2,000 residents.

Because of the incident, 24 out of the 37 tanks were destroyed, 6 fixed roofs were found 50 m away from tanks. All the cooling and fire protection devices were put out of order with the pipes thrown to tens of meters of distance. Property damage included 12 large buildings, 448 small industrial units and 220 houses, some of which were totally destroyed. A highway connection nearby was heavily damaged. About 800 firefighters with 166 pieces of mobile equipment were involved in emergency operation, consuming four-hundred and sixty tons of foam.

Marsh's "The 100 Largest Losses[21]" also describes the Naples incident stating, "*The devastating explosion destroyed the terminal buildings and extensively damaged nearby industrial and residential structures.*"

Lessons learned from this incident include: 1) releases of gasoline at ambient conditions can lead to violent open-air explosions, 2) discharges from a height and a spill down the side of a tank will help formation of a vapor cloud, and 3) damage from such a VCE can be widespread.

URAL MOUNTAINS, SOVIET UNION, 1989

An incident occurred in the Ural Mountains, in the former Soviet Union in June 1989[14]. A 28-inch diameter pipeline carrying Natural Gas Liquids (NGLs) from western Siberia to Ufa was reported to be leaking for several days. NGL is usually composed of varying concentrations of propane, butanes, pentanes plus higher molecular weight hydrocarbons. Instead of investigating, operators increased pumping rate. There was a strong smell of gas for a number of hours before the explosion. The split in the pipeline was later found to be 1.5–2 meters. The leak was about 0.8 km from the Trans-Siberian Railway. Trees are believed to have provided the necessary confinement. The vapor cloud made its way to the railway and two trains coming from opposite directions went into the fog-like gas cloud. Two explosions took place in quick succession causing a huge 1,600 meter wide wall of flame–carriages on trains were blown sideways, wooden carriages burned out in 10 minutes–over 600 people were killed. Trees were flattened within 4 km of the blast and windows were broken 13 km away.

One of the key lessons learned from this incident is that you cannot ignore trees when considering open-air explosions.

ST HERBLAIN, FRANCE, 1991

On October 7, 1991, a vapor cloud explosion occurred in a petroleum depot in Nantes, France[16]. At about 4 a.m., at the retention basin, a white cloud formed and spread toward the road-tankers park. Its advance was, nearly 15 minutes to extend 50 meters and to reach the road. Simultaneously, its depth was increasing in size to reach approximately 1.5 meters.

In addition to 100% humidity and an ambient temperature of 5°C, the wind speed was less than 1 m/s and the atmosphere was stable thus inducing the vapor cloud to stay in place and entrain air gradually until it was ignited.

A leak on a transfer line occurred and a continuous leak of gasoline produced a large vapor cloud, of at least about 23,000 m^3, which covered a part of the storage area, a road and the parking. It was noticed that part of this cloud was made of aerosols. About 20 minutes later, the vapor cloud was ignited. An explosion resulted. As a consequence of the VCE, tanks were damaged and road-tankers were turned over and burned and windows were broken within a radius of 2 km.

Lessons learned from this incident include, 1) gasoline at ambient conditions can generate a vapor cloud of sufficient size resulting in a violent VCE, and 2) damage from such a VCE can be widespread.

LAEM CHABANG, THAILAND, 1999

In 1999, in Laem Chabang, Thailand, gasoline release from an overfilling operation from the storage tanks of the refinery resulted in a VCE causing eight fatalities and significant property damage[29]. The blast was felt several km away.

The lessons learned from this incident include: 1) Gasoline at ambient temperature can generate a vapor cloud of sufficient size to support a VCE, and 2) such a VCE can cause fatalities and significant property damage over a wide radius.

THE MECHANISM OF VCE'S WITH VIOLENT OVERPRESSURES

SIZE OF THE VAPOR CLOUD

Bakke and Hansen[30] in their article *"Probabilistic analysis of gas explosion loads"* refer to three key things in determining the intensity of overpressures resulting from an explosion: congestion, confinement and gas cloud size. The effect of confinement and congestion is discussed in later sections. In this section, the effect of the size of the vapor cloud is explained.

By all accounts, the vapor cloud that resulted from the overfilling operation at the Buncefield site was a massive cloud released over a relatively long period of time. The size of the cloud has a direct impact on several factors and is therefore a vital consideration in determining the consequences of an explosion. A larger cloud will contain more fuel and thus a greater amount of energy available for conversion to explosion energy. In addition, a larger cloud has a higher possibility of encountering confinement or congestion, both of which have exacerbating effects with regard to the explosion. As explained in more detail in the following sections, confinement creates higher overpressures by compartmentalization of the cloud, allowing pressure to build in a controlled volume before breaking confinement. A larger vapor cloud will migrate farther and has the opportunity to encounter more congestion which must be considered to create turbulence and impact the explosion strength. There may be trees, equipment, structures or other obstacles, some distance away from the source of the leak. Thus predictions based simply on the immediate surroundings (which may be flat and uncluttered) of the tank will miss this danger. A larger cloud also increases the possibility that the cloud will encounter ignition sources, possibly high-energy ignition sources. These factors are well established in the industry and are included in the Hazardous Installations Directorate ("HID") guidelines (section 4, page 3)[31], which specifically refer to the importance of the size of the vapor cloud with respect to the total energy, more ignition sources, congested areas and interactions.

The obvious result of these considerations is that a vapor cloud that reaches the car park of Northgate must be assumed to encounter confinement and obstructions, and to have developed turbulence during this process.

CONGESTION, GEOMETRY AND TURBULENCE

Congestion is created by obstructions and closeness of those obstructions. Also the geometric shape of those obstructions plays a significant role in determining congestion. During a gas explosion, obstructions obstruct the flame front causing turbulence.

Turbulence plays a role in creating large overpressures. Turbulence plays a role at two different stages: (1) the mixing of air with the vapor; and (2) propagation of high flame speed. Both of these factors can have an impact on overpressure. The role played by turbulence in mixing of the air with vapor has been discussed earlier. A discussion is now presented of the effect of turbulence on propagation of high flame speed leading to high overpressures.

The blast effects produced by VCEs are determined by the speed of flame propagation. The faster the flame propagates through the flammable cloud, the higher the overpressure in the cloud will be which, in turn, will increase the blast effects outside the cloud. This implies that the mode of flame propagation is very important. As stated in p. 5.12 of the TNO Yellow Book[32],

> *"When ignition occurs in a flammable cloud at rest, the flame will start to propagate away from the ignition point. The combustion products expand causing flow ahead of the flame. Initially this flow will be laminar". "Under laminar or near-laminar conditions the flame speeds for normal hydrocarbons are too low to produce any significant blast overpressure . . .the vapor cloud will simply burn and the event is described as a large flash fire.*
>
> *Therefore an additional condition is necessary for vapor cloud explosions with pressure*

> *development: the presence of turbulence. Research testing has shown that turbulence will significantly enhance the combustion rate in deflagrations.*"

Turbulence may arise in a vapor cloud explosion accident scenario in various ways. Prior to ignition it plays a role in the release mechanism of flammable material itself, mixing being induced by obstructions. After ignition, turbulence plays a role by the interaction of the flame front with obstacles present in a congested area. These mechanisms may cause very high flame speeds and as a result, strong blast pressures.

The turbulence is very important for how fast the flame can propagate in a gas cloud. The turbulence will wrinkle the flame front and increase diffusion of heat and mass and thereby cause higher burning rate (p. 22 of GEH[17]).

In most accidental explosions the laminar flame will accelerate and transit into a turbulent deflagration (i.e., turbulent flame), since the flow field ahead of the flame front becomes turbulent. The turbulence is caused by the interaction of the flow field with process equipment, piping, structures etc. (p. 45 of GEH[17]).

The flame speed and explosion pressure will strongly depend on the gas cloud and the geometrical conditions within the cloud (i.e., process equipment, piping etc.) or geometries confining the cloud (i.e., buildings etc.). To predict the flame speed and explosion pressure for a deflagration is not a simple task, even if scenario parameters such as cloud size, fuel concentration and ignition point are known (p. 40 of GEH[17]).

In the extreme, the turbulence can be a contributing factor to cause the flame propagation mode to change suddenly from deflagration into detonation. This mode of flame propagation is attended by propagation speeds in excess of the speed of sound (twice to 5 times the speed of sound) and maximum overpressures of about 18 bar. Once the speed of sound is exceeded, turbulence is no longer necessary to maintain its speed of propagation, which means that unobstructed and/or quiescent flammable parts of a cloud may also participate in the production of blast. As noted in the TNO Yellow Book[32] at p. 5.12 "*It should, however be emphasized that for a detonation to propagate, experimental indications suggest that the flammable part of the cloud must be rather homogeneously mixed. For this reason a vapor cloud detonation of the cloud as a whole, although is a possibility, is a most unlikely phenomenon to occur*".

The Yellow Book[32] goes on to say on p. 5.12 "*The likelihood of occurrence of deflagration and a detonation is also influenced by the ignition process. Hydrocarbon-air mixtures need a high-explosive charge as the ignition source for direct initiation of a detonation. Therefore, deflagrations are the most common combustion mode and detonations arise from a Deflagration to Detonation Transition (DDT)*".

The Yellow Book[32] also notes on p. 5.18,

> "*The obstacles and structures present in the vapor cloud, acting as turbulence generators, play a very important role in the development of the process. A change of the obstacle configuration in the flow path changes the acceleration process. An absence of turbulence generators will lead to a reduction in flow speed and will decelerate the flame. Acceleration of the flame is influenced also by the measure of obstruction and confinement of the expansion flow. Due to the restricted expansion possibilities of the combustion products a one-dimensional flow (in a pipe) causes more acceleration than a two-dimensional (between parallel plates) or a three dimensional flow with no confinement at all.*"

As stated at p. 64 of the GEH[17], small changes in the geometry can lead to order of magnitude changes in explosion pressure.

A series of experiments (MERGE[33] & EMERGE[34]), were performed by Mercx and others in the 1990s to attempt to derive a correlation between the size of the overpressure with the size and density of obstructions in a congested area. The research allowed some level of direct guidance to be used by practitioners when determining the explosion strength based on the blockage in a congested area, the obstacle diameters, and the flame path length.

More recently there has been extensive work using computational fluid dynamics (CFD) tools for risk assessments. In this way the impact of congestion on the explosion development can be directly observed given a wide range of potential scenarios. This research has shown that a much greater level of detail can be obtained using this methodology than any previous method and that a more realistic understanding of the hazards of congestion[35–37].

In considering the most likely scenario, one must deal with the effects of vegetation and trees, other sites of congestion/turbulence/confinement within the cloud's footprint, and turbulence being a circular process. The mechanism of flame acceleration caused by repeated obstacles constitutes a strong positive feedback loop.

Although with a high-energy ignition source the cloud can become turbulent from the onset. In fluid dynamics we divide the flow into laminar and turbulent regimes. Laminar flow means that the fluid flows in laminars or layers, with no disruption between the layers, while turbulent flow is characterized by an irregular random fluctuation imposed on mean (time-averaged) flow velocity (p. 512 of TNO Yellow Book[32]).

CONFINEMENT

In comparison to congestion, confinement occurs when the released gas is completely or partially trapped in a confined area.

Confined gas explosions are explosions within tanks, process equipment, pipes, in culverts, sewage systems, closed rooms and in underground installations. Confined explosions are also called internal explosions. Typical for this kind of explosion is that the combustion process does not need to be fast in order to cause serious pressure build-up. The danger of a vapor cloud getting into enclosed culverts, drains and the like gives rise to the problem of confinement. A dense gas can move along the ground, disperse slowly and drift into buildings or other confined areas. In the event of drift into tunnels or culverts, this is equivalent to an internal explosion. This kind of scenario is potentially possible in a site like Buncefield and thus lends itself to the foreseeability of an explosion with large overpressures.

Confinement includes total confinement and partial confinement. Total confinement refers to situations where the cloud is completely confined in an enclosed area. In contrast, partial confinement refers to situations where a certain degree of confinement is provided by structures or obstacles, such as tanks or buildings. The confinement, partial or total, is conducive to serious pressure build-ups. Confinement can also lead to the possibility of a bang-box where you have an enclosed structure where you have an explosion. At the least, such a bang-box explosion has the potential to create a high-energy ignition source. A high-energy ignition source is an important contributing factor to the strength of an explosion. A bang-box is a confined explosion that vents or breaks out of confinement at some point in the pressure rise.

The impact of the ignition energy and location can play a significant role in the resulting overpressure generated by a VCE. Literature indicates that locating the ignition source in a more favorable location can decrease the overpressure by an order of magnitude, while increasing the strength of the ignition source can cause measurable overpressures even in uncongested areas[38, 39].

Research has shown that the local non-homogeneity of the pressure field, produced by the presence of small-size obstacles plays a role in creating overpressures. In some cases, this effect is very marked resulting in higher overpressures causing local effects of the explosion that can be very destructive (p. 10 of Russo et al.[26])

DETONATION

A detonation takes place when the reaction front (flame front) is limited only by the rate of reaction and advances into the unreacted (unburned) vapor cloud at or greater than the sonic velocity of the fuel/air mixture at its initial temperature and pressure. Several factors influence the initiation of a detonation, or the transition of a deflagration to a detonation. These factors include the ignition source strength, the geometry of the obstructions and, the fuel/air turbulence.

In order to produce a direct initiation of a detonation in a hydrocarbon/air vapor cloud, the class of ignition source needs to be a higher energy than that for a deflagration. In general detonation energies need to be on the order of 10^6 J, whereas deflagration energies can be as low as 10^{-4} J. Ignition sources of this class include high-energy electrical discharges (lightning), condensed phase or energetic substances (blasting cap or TNT).

An incidence of this is provided by a "bang-box" effect, created by a confined space explosion enclosed in a larger vapor cloud which can lead to a detonation. In this case a shock wave is created in the confined area and as it spreads into the unconfined flammable area a highly turbulent compression zone is created that will propagate the detonation wave.

DEFLAGRATION TO DETONATION TRANSITION (DDT)

An alternative way in which a detonation can arise is by transition of a deflagration into a detonation. This occurs when the flame front passes through congested areas and reaches a certain velocity. In the extreme, the turbulence can be a contributing factor to cause the flame propagation mode to change suddenly from deflagration into detonation. This mode of flame propagation is attended by propagation speeds in excess of the speed of sound (twice to 5 times the speed of sound) and maximum overpressures of about 18 bar. Once the speed of sound is exceeded, turbulence is no longer necessary to maintain its speed of propagation, which means that unobstructed and/or quiescent flammable parts of a cloud may also participate in the production of blast.

MOST LIKELY SCENARIO AT BUNCEFIELD

TURBULENCE

The mechanism of the fuel release and drop from height leads to vapor release and by the time the release hits the ground, most of the vapor is formed. The turbulence of the release itself created turbulence that caused air entrainment. As the vapor rolled over the bund further entrainment was caused by onsite congestion. The air entrainment process was enhanced as the vapor reached Buncefield Lane and Cherry Trees Lane where further mixing was facilitated–because of both the presence of trees and also the fact that both the lanes had dips. Therefore, instead of the vapor cloud being low when it reached the car park, the vapor was mixing with air at fairly consistent levels in height. After ignition, the well mixed fuel-air vapor cloud will also have higher flame speeds caused by the turbulence thus further exacerbating the intensity of the explosion. This explains the forces that were seen in the car park and the resulting damage that was created.

IGNITION

- Two most likely candidates for ignition source were the pump house and the generator cabin.
- There is a possibility that either of these could have been internal explosions providing a high-energy ignition source.

CONFINEMENT AND CONGESTION

The following provided confinement and congestion.

- The pump pad as well as other onsite equipment provided onsite congestion.
- The buildings, and trees all acted, to some degree, as baffles within the cloud.
- There is no material difference between lines of trees and pipework assemblies as far as being needed to be considered as congestion.
- The buildings on the western side of the car park were effectively holding up the vapor thus providing a degree of confinement.
- There were also some walls (within the Northgate car park and to the Northeast of Bund A).
- All of the tanks around Tank 912 would have provided a degree of confinement.

POSSIBILITY OF INTERACTION

The possibility of more than one explosion where the interaction between explosions contributed to an overall increase in overpressure greater than the overpressure generated by any single explosion cannot be ruled out.

THE POSSIBILITY OF DETONATION

The possibility of detonation though very low cannot be ruled out. Detonation could have been caused by one of the following mechanisms.

- Direct detonation (an example of which is a bang-box).
- Deflagration to detonation transition that occurs when the flame front encounters congestion causing the flame velocity to increase to speeds 2 to 5 times the speed of sound.

CONCLUSIONS

In the final analysis, there was nothing new, unexpected or unforeseeable about what happened at Buncefield, in terms of the range and degree of damage. It was entirely the sort of event which was liable to occur, if not as a probability following the escape, certainly as a distinct possibility. This conclusion is quite elementary, once you assume the escape of gasoline from tank 912 which occurred. Given the release scenario in the Buncefield incident and given evidence of past incidents, the extent of damages should have been anticipated as a realistic possibility.

While no two incidents are exactly similar, it has been demonstrated time and again in the past that incidents similar to the Buncefield incident have occurred with devastating consequences.

The safety performance of an organization depends on a complex system of multiple layers of protection. These layers of protection include design, construction, operation, maintenance, prevention systems, and emergency response and mitigation systems. Each one of these layers of protection deserves attention to detail and consideration of the extent of the hazard and potential consequences from different scenarios. In addition to these multiple layers of protection, industry must develop and implement management systems to learn from incidents and capture those lessons into design, procedures, training, maintenance, and other programs. Organizations must also develop and implement good incident investigation procedures to find “root causes” and all the other management systems necessary to take advantage of the lessons learned.

Over the long term, safety performance cannot be improved by measuring and concentrating on trailing indicators only. It is very important to be able to identify and track leading indicators. Leading indicators provide an early warning system for trailing indicators. More importantly, management and reduction of leading indicators should automatically lead to reductions in trailing indicators. The relationship between leading and trailing indicators is reasonably well understood and industry must develop and implement management systems to take both into account as efforts are made to improve safety performance.

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